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Fiber design and realization of point-by-point written fiber Bragg gratings in polymer optical fibers

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ABSTRACT

An increasing interest in making sensors based on fiber Bragg gratings (FBGs) written in polymer optical fibers (POFs) has been seen recently. Mostly microstructured POFs (mPOFs) have been chosen for this purpose because they are easier to fabricate compared, for example, to step index fibers and because they allow to tune the guiding parameters by modifying the microstructure. Now a days the only technique used to write gratings in such fibers is the phase mask technique with UV light illumination. Despite the good results that have been obtained, a limited flexibility on the grating design and the very long times required for the writing of FBGs raise some questions about the possibility of exporting POF FBGs and the sensors based on them from the laboratory bench to the mass production market. The possibility of arbitrary design of fiber Bragg gratings and the very short time required to write the gratings make the point-by-point grating writing technique very interesting and would appear to be able to fill this technological gap. On the other end this technique is hardly applicable for microstructured fibers because of the writing beam being scattered by the air-holes. We report on the design and realization of a microstructured polymer optical fiber made of PMMA for direct writing of FBGs. The fiber was designed specifically to avoid obstruction of the writing beam by air-holes. The realized fiber has been used to point-by-point write a 5 mm long fourth order FBG with a Bragg wavelength of 1518 nm. The grating was inspected under Differential Interferometric Contrast microscope and the reflection spectrum was measured. This is, to the best of our knowledge, the first FBGs written into a mPOF with the point-by-point technique and also the fastest ever written into a polymer optical fiber, with less than 2.5 seconds needed.

Keywords: Polymer fiber, Bragg grating, Direct writing

1. INTRODUCTION

Many important industrial applications have found their solution in fiber-optic sensors based on fiber Bragg gratings (FBGs).^{1,2} Up to now the fiber material used has been silica, because of its low loss and resistance to high temperatures. However, for particular purposes, as strain sensing, polymer optical fiber (POF) FBGs are better suited because of the low Young's modulus and high failure strain of polymer compared to silica.^{1,3}

Various configurations have been used to write fiber Bragg gratings in both step index and microstructured polymer optical fiber: continuous wave (CW) UV illumination in a ring interferometer⁴ and UV phase-mask.⁵⁻¹² The required writing time is usually of 30-100 minutes for step index fibers^{5,6} and 60-270 minutes for mPOF.⁷⁻¹¹ Shorter writing times have been shown with a specially photosensitized fiber.¹² Moreover in the microstructured POFs (mPOFs) the resulting gratings are also relatively weak. The long inscription time is a result of the relatively weak photosensitivity of polymers. The air-hole microstructure obstructs the core mPOFs and therefore contributes to the writing time increase, compared to solid POFs, and to the relatively weak gratings.¹³⁻¹⁵ Long writing times is a serious problem for applications requiring mass production.

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Point-by-point grating writing, with high intensity ultrashort laser pulses, has been previously used to overcome the low photosensitivity of polymer waveguides.^{16–18} This approach has been demonstrated also in step index silica fibers,^{19,20} and in silica waveguides.²¹ Advantages of direct-writing are also: flexibility in the grating design,²² and avoiding the expense of the phase mask and of use of dopants or hydrogenation to increase the photosensitivity. However, the problem of obstruction by the microstructure still needs to be overcome.

It would be possible to fill the holes with a material with similar index to the host to overcome scattering by the microstructure. However this is not trivial since filling the holes can be difficult to achieve in practice and significantly reduces the strong confinement achievable in air-filled microstructures²³ and it would be difficult to get the liquid out of the fiber.

The first grating point-by-point written in a simple silica microstructured fiber was recently demonstrated by Geernaert *et al.*²⁴ The fiber used is made by only two parallel layers of holes. Having only one layer of holes to go through during writing minimized scattering and diffraction of the writing beam. However there is still a tradeoff between confinement of the guided mode and access to the core by the grating writing beam.

In this paper we report on the design of a mPOF specifically for direct writing, and on the investigation of the writing parameters for polymers and on the grating realization.

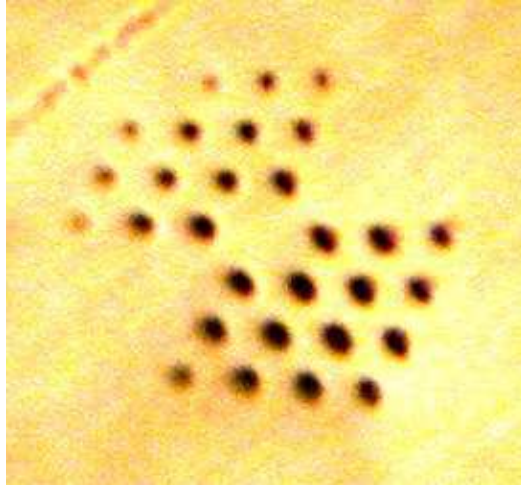


Figure 1. Cross section of the realized mPOF structure designed for direct writing.

2. FIBER DESIGN

The fiber design aimed to let the writing focused laser beam to pass between the air-holes in order to encounter minimal scattering before reaching the core. To serve the purpose 3 holes were removed creating an “opening” in the 3 ring hexagonal microstructure (see Fig. 1-2). As the fiber was symmetric, 6 holes in total were removed. In this way access for the focused 800 nm laser beam was created through the microstructure on both sides. The hole to hole distance was made so that the beam could also pass the first ring of holes without facing any interface. The spot size of the focused beam was estimated just above 1 μm and, as we aim for a hole to pitch ratio of 0.42 (condition to make the mPOF endlessly single mode with all holes present in the cladding²⁵), a minimum pitch of 2 μm was required. The mode was simulated (with the commercial software COMSOL) and the confinement loss were calculated. Since the material has about 100 dB/m loss at 1550 nm,³ the resulting loss of the order of less than 1 dB/m were considered negligible.

3. FIBER FABRICATION

The microstructure of fabricated fiber is shown in Fig. 1. The fiber has a diameter of 130 μm and a slightly asymmetric microstructure with hole diameters between 1 and 1.5 μm . The pitch is 3.5 μm , resulting in a hole to pitch ratio between 0.29 and 0.43.

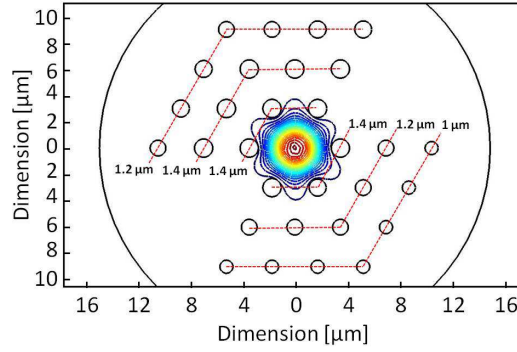


Figure 2. COMSOL simulation of the guided mode in the fiber. The simulated structure has a pitch of $3.5 \mu\text{m}$ and hole diameters varying from 1 to $1.4 \mu\text{m}$ in order to match as much as possible the real structure.

A simulation of the realized fiber was also made in order to estimate the guiding properties. In the simulation a pitch of $3.5 \mu\text{m}$ and hole diameters varying from 1 to $1.4 \mu\text{m}$ were used (as shown in Fig. 2) in order to match as much as possible the real structure. The fundamental mode for a wavelength of $1.52 \mu\text{m}$ is shown in Fig. 2. The simulated fundamental mode has an effective refractive index of $n_{eff}=1.48037$ (using 1.49 as material refractive index) and from the imaginary part a confinement loss of 0.67 dB/m is calculated.

4. GRATING WRITING

Before writing the grating, slab samples of PMMA were investigated in order to determine necessary pulse energy to use during writing.

4.1 DAMAGE INVESTIGATION

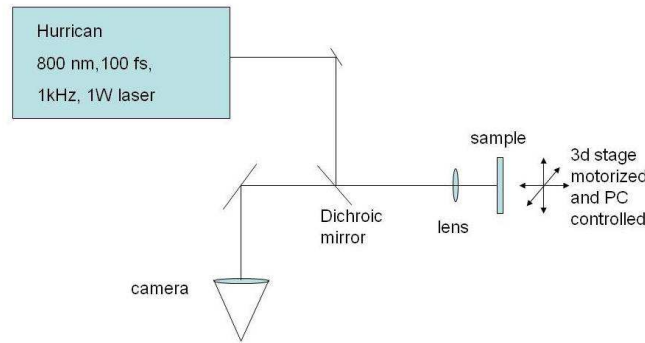


Figure 3. Schematic of the set-up used for point by point writing.

The grating writing set-up²⁶ is shown in Fig. 3. A regeneratively amplified, low-repetition rate, Ti:sapphire femtosecond laser system (Hurricane, Spectra-Physics) was used to produce the refractive index change. The output of the laser has 100 fs pulses with a central wavelength of 800 nm . A series of neutral density filters at the output of the laser was used to reduce and control the pulse energy. The beam was then reflected by a dichroic mirror, which allowed to observe the writing process with a CCD camera. After the dichroic mirror the light beam was focused with a $40\times$ objective lens into the sample. The sample was mounted on an automated and computer controlled 3 axes translation stage (Aerotech FA-130, Aerotech ABL200) that can move with 200 nm resolution.

The test have been run by inscribing a series of lines of damages spots, and for each line one parameter was changed. two different parameters have been investigated: the pulse energy and the writing speed. Moreover

various thermal treatments were applied to investigate the effect of residual strain. A series of 6 x 4 lines have been written every time. In particular, the test set used 6 different energies (100, 90, 80, 70, 60, 50 nJ) and 4 different spacing between the spots (5, 3, 2, 1 μm). The laser repetition rate used is 500 Hz and the different spacing was realized by using the following speeds for the stage: 150, 90, 60, 30 mm/min. Single shot damages spots, 170 μm below the sheet surface, were used.

Fig. 4 the resulting DIC image of the test. It is possible to see that the 1 μm spaced spots can almost not be distinguished, creating a full line. This factor poses a limitation on the grating period.

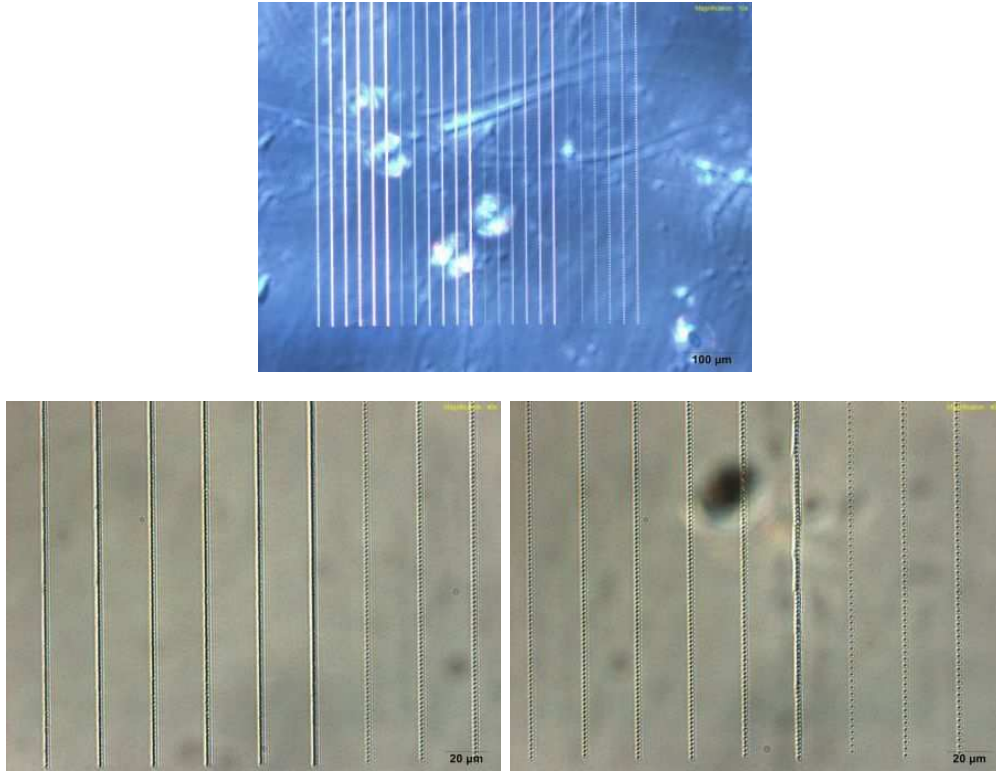


Figure 4. DIC microscope image of the spots. The image top image is an overview of the 6 x 4 lines. The images in the bottom are zoom in of the 1 μm (left) and 2 μm (right) spaced spots.

The slabs were then placed in the oven (100C) overnight. The spots were then remeasured and a second set was then written. The slabs were again placed in the oven for 5 days and both set were remeasured. In Fig. 5 the result of the two annealing process is showed for the 1 μm spaced spots. Some stress line can be seen. The spots with larger spacing did not show significant difference.

After one day in the oven the writing was repeated. Fig 6 shows the resulting spots and the same spots after 5 days annealing.

In this situation is possible to see how the low energy spots do not overlap, showing a smaller diffusion of the damage area. No significant difference can be seen after annealing.

4.2 FBG

After choosing 75 nJ as energy. Grating writing in the optical fiber was performed. The alignment of the fiber was done visually with a CCD camera

A 4th order grating at $\lambda_B=1520$ nm was targeted. This grating order was the minimum for which two consecutive spots (with diameter around 1 μm) would not overlap (since the fiber was not preannealed). We find

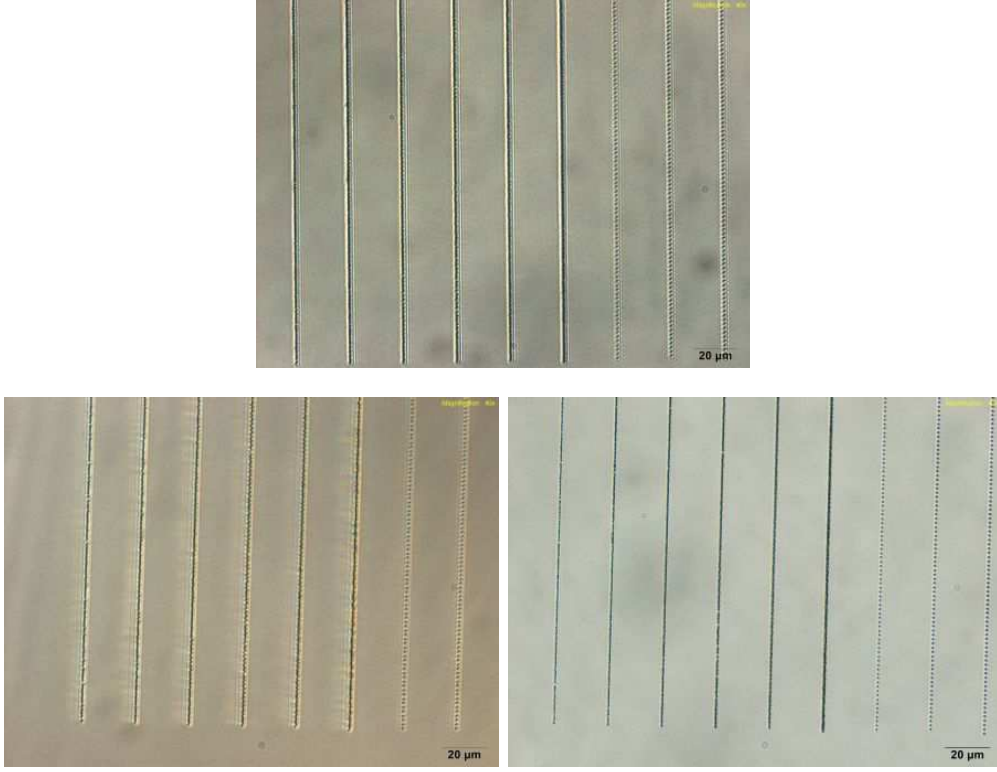


Figure 5. DIC microscope image of the spots. $1\mu\text{m}$ spaced spots (top). Bottom: one night at 100 deg (left) and 5 more days at 100 deg (right).

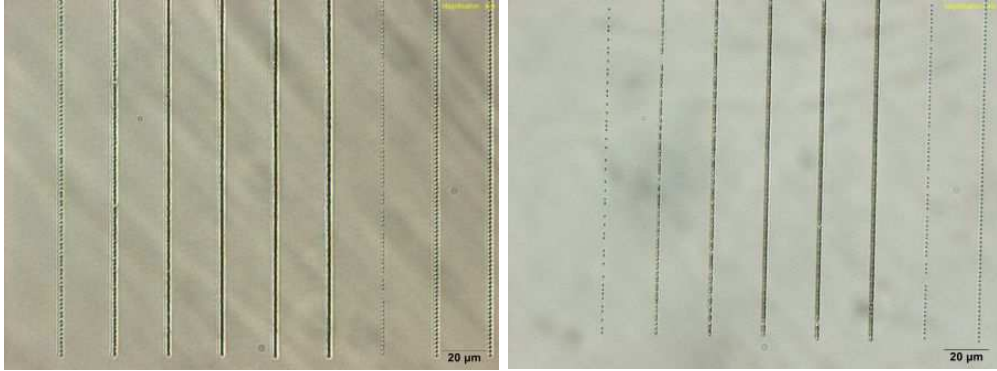


Figure 6. DIC microscope image of the spots. $1\mu\text{m}$ spaced spots written after annealing (left) and the same spots after 5 days annealing (right).

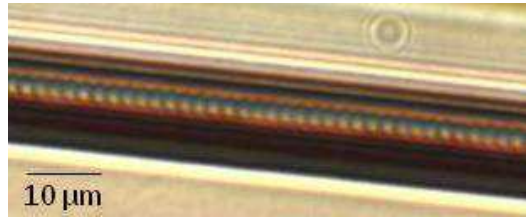


Figure 7. DIC microscope image of the FBG. The image was taken with a 40x magnification lens. A modulation with about $2\mu\text{m}$ period can be seen at the center of the fiber and in particular at the center of the microstructure.

a grating period of $\Lambda = \frac{4\lambda_B}{2n_{eff}} = 2.053\mu\text{m}$, using the calculated $n_{eff}=1.48037$. We then calculate a necessary

translation speed of $2.053 \mu\text{m} \times 1\text{kHz} = 2.053 \text{ mm/s}$, calculated for the case of single pulse per spot.

The fiber was examined afterwards under a differential interference contrast (DIC) microscope (Olympus). The resulting image is shown in Fig. 7. From the image a clear modulation of the refractive index is visible. The modulation period is around $2 \mu\text{m}$, which is in agreement with the design spacing.

A reflection spectrum was also measured and will be presented.

5. CONCLUSIONS

In conclusion we have shown a new fiber design, and its realization, for direct writing of FBGs in microstructured fibers. We showed investigation of the spots on a polymer slab for different spacing, energies, and annealing conditions. We also show the grating writing in the designed fiber. The grating is a fourth order grating resulting with Bragg wavelength at 1518.67 nm .

The proof that the direct writing technique can work for mPOFs could solve one of the crucial problems of mPOF FBG fabrication, i.e. the long writing time, which is generally above 60 minutes for mPOFs.¹

We note that direct writing could allow grating writing in fibers made with non-photosensitive materials, such as low loss perfluorinated POFs.³

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